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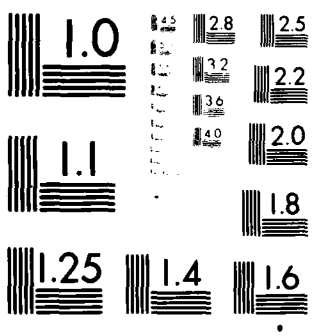

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FINAL REPORT TO THE
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

on

RESEARCH ON UNSTEADY COMBUSTION PROCESSES

Grant AFOSR-76-3104
From 1 October 1975 to 30 September 1981

Submitted by

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Assistant Professor
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Princeton, New Jersey

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Velocity measurement
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Aluminum agglormeration
Droplet break-up
Cross-flow velocity effects

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Dynamic responses of rocket motors and aluminum combustion under rocket motor conditions were investigated and the results related to combustion stability and motor efficiency. The first part of the study is centered around the Forced Longitudinal Wave Motor, which was developed to investigate the dynamic responses of high performance rocket motors in which externally excited longitudinal pressure and velocity waves produce couplings with propellant combustion processes. A linear analysis revealed that the imaginary part of the velocity coupling response can be deduced from the phase angle between the nozzle- and

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TABLE OF CONTENTS

1.0 INTRODUCTION AND TECHNICAL OBJECTIVES

Rocket motor chamber flow and propellant combustion behavior, particularly as they relate to combustion stability, aluminum burning, and combustion efficiency in solid rockets, were investigated. Experimental techniques and the analytical models were developed to take into account the couplings such as unsteady chamber flow, nozzle flow, dynamic burning, and velocity coupling. Aluminum agglomerates were investigated as they form on the propellant surface, and after they leave the propellant surface and enter the high velocity port flow and nozzle, using improved high-speed photographic techniques. Since the results are being obtained using rocket motor configurations and high energy propellants, the experiments produced propellant/chamber response characteristics that, in several cases, were readily relatable to developmental rocket motors.

This final report very briefly summarizes approaches and results to further the scientific understanding of propellant combustion and chamber flow behavior, particularly as they relate to metal combustion and to unsteady combustion and flow in high-performance rocket motors. As an example of the practical objectives, the results of such research can be important inputs to procedures to optimize propellant geometry, operating pressure, propellant formulations, etc. Also, the results can lead to generalizations of this knowledge for applications to new, advanced propellants and new rocket motor concepts. An equally powerful motivation for the research is the scientific one. The phenomena that occur in many unsteady flame and reacting flow field situations have not been adequately explained

in terms of physical models and theories. In this sense, the problems of unsteady flow and combustion processes in solid rocket chambers represent a scientific challenge. Solutions to these problems have important implications even for the supposedly well-understood cases of steady state flames. All of this suggests that the exploration of unsteady phenomena will lead to a much more advanced understanding of the physicochemical and fluid mechanical bases of flames and chamber flows.

2.0 RESEARCH - FINAL STATUS

2.1 Solid Propellant Rocket Motor Response Functions

Research using the Forced Longitudinal Wave (FLW) motor was conducted to determine whether dynamic pressure and velocity measurements inside a solid rocket chamber can be utilized to deduce simultaneously the propellant pressure-coupled and velocity-coupled responses. As indicated in Figure 1, the novel aspect of the approach is that the FLW apparatus establishes and measures both longitudinal pressure and velocity oscillations in rocket chambers. A linear analysis of steady-state oscillations within rocket chambers revealed that oscillatory pressure measurements (at the head and nozzle ends) plus midchamber oscillatory velocity measurements provide sufficient information to deduce both real and imaginary parts of the overall response functions. In particular, the linear model revealed that (1) the pressure amplitude gain is almost solely a function of the real part of the velocity-coupled response, (2) the phase angle between head and nozzle-end oscillations is almost solely a function of the imaginary part of the velocity-coupled response, and (3) a precise knowledge of the pressure-coupled response is not required for an accurate determination of the velocity-coupled response.

The midchamber velocity measurement was achieved by means of a magnetic flowmeter (Figure 2a), a technique previously unproven within unstable solid rocket chambers. The velocity measurement was utilized to deduce the real part of the pressure-coupled response as a function of frequency for a single 86% solids AP/HTPB propellant (Figure 2b). The real and imaginary parts of the velocity-coupled responses (Figure 2c) were

deduced as a function of frequency by means of the two pressure measurements for two high solids density AP/HTPB propellants. The real and imaginary parts of the velocity-coupled response were obtained at a single frequency for ANB-3066 provided for the AFRPL velocity-coupled round robin. The results appear to be consistent with the previous knowledge of response function characteristics.

The FLW motor results are the first successful measurements of propellant response functions within a rocket motor environment. The response functions which were obtained and analyzed as part of this research are consistent with the methodology being used in the state-of-the-art stability prediction computer programs, i.e., they were deduced using the same basic assumptions and represent overall values for the propellant/motor system. The measured values are device dependent, since the velocity coupled responses are very dependent on the flow field in each individual motor. However, other aspects of the measurements are not dominated by difficult-to-measure parameters and corrections.

2.2 Aluminum Combustion in Solid Rocket Motors

Knowledge of Al/Al_2O_3 agglomerate formation and breakup is of fundamental importance to the application of aluminized solid propellants. Since aluminum is added to increase specific impulse, its effectiveness depends on maximizing completeness of combustion prior to ejection from the nozzle exit plane. Combustion and agglormeration processes of aluminum particles emitted from the surface of aluminized propellants were studied under rocket motor, cross-flow conditions as well as strand-burning conditions. Highspeed, color photographs (5000 fr/s) were taken of Al/Al_2O_3 agglomerates forming on the surface, moving along the surface, entering the flow field, and passing through a nozzle. Particle size and velocity data were obtained for two series of propellants: double-base propellants with up to 13% Al and high solids AP composite propellants with up to 18% Al.

Propellants often produce agglomerates which burn slowly compared to rocket motor stay times. Break-up under nozzle flow conditions has been postulated as the mechanism leading to more complete combustion and, thus, acceptable specific impulses. However, prior to this research the actual break-up and the conditions which produce it had not been observed. An experiment was devised in which burning aluminum agglomerates in the 200 to 1200um diameter range were photographed as they passed through a subsonic nozzle (0.1 to 0.2 Mach number). The experiments revealed that as the flow accelerated, the velocity differential between the agglomerates and the gas deformed the agglomerates causing them to break into relatively small droplets which burn much more rapidly. A break-up criterion based on a maximum Weber number (a ratio of shear to surface tension forces) was developed. Break-up

occurred whenever the maximum Weber number exceeded approximately 27 (see Figure 3).

In addition to obtaining an improved understanding of the breakup phenomena, the results of this research have direct applications to rocket motor performance considerations. Calculations were performed to illustrate rocket nozzle and agglomerate size conditions that lead to breakup. Rocket motor performance conclusions (for specific systems) cannot be based only on dimensions of agglomerates leaving the propellant surface, but must consider the fraction of the agglomerates which may be too small to break up under nozzle shear flow conditions and too large to burn efficiently prior to passing through the nozzle.

The agglomeration processes of an aluminized double base propellant (NC/MTN) were studied under rocket motor, cross-flow conditions. High-speed, color photographs ($\sim$ 2000 fr/s) were taken of burning Al/Al_2O_3 agglomerates forming on the surface, moving along the surface, and entering the flow field. As an example, a propellant containing 6 μm Al burning at 7 MPa and 6 m/s cross flow produced a mean agglomerate size of about 250 μm. Analysis of size distributions of the agglomerates leaving the surface revealed that the following parameters decrease with increasing pressure: collision frequency on the surface, the agglomerate stay time on the surface, and mean agglomerate size. Increasing the cross-flow velocity decreased the mean agglomerate size (see Figure 4). The propellant which contained the larger aluminum particles (50 μm vs 6 μm) burned without the aluminum igniting or agglomerating on the surface.

Aluminum powders added to conventional rocket propellants burn either as single particles or agglomerates which contain hundreds or even thousands of the original particles. Combustion efficiency and acoustic stability characteristics are very dependent on the final Al/Al_2O_3 particle size injected into the chamber flowfield. High-speed photographs of burning homogeneous propellants provided data on agglomeration size and visualization of the flow processes as a function of pressure (1 to 10 MPa), initial particle size (5 to 100 μm), and aluminum mass fraction (0.1 to 13%). Photomicrographs of extinguished surfaces revealed the importance of particle accumulation in a thin mobile reaction layer adjacent to the burning surface. A model was developed that interpreted data and observations from several sources. The model accounts for accumulation of aluminum particles in the mobile reaction layer, retention of particles by surface tension forces, melting, and ignition at the surface. The following agglomeration and particle behavior items are categorized: decreasing agglomerate size with increasing pressure, minimum mass loading required for agglomeration, prominent agglomeration for particles with diameters less than the reaction layer thickness and sharply reduced agglomeration for larger particles (see Figure 5). The model provides an approach for controlling and interpreting agglomerate size behavior.

3.0 PUBLICATIONS, PROFESSIONAL PERSONNEL AND INTERACTIONS

3.1 Publications

The following publications were prepared:

"Aluminized Solid Propellants Burning in a Rocket Motor Flow Field," AIAA Journal, Vol. 16, No. 7, July 1978, pp. 736-739, L.H. Caveny, A. Gany and M. Summerfield.

"Flow Field Effects on Combustion of Aluminized Propellants," Proceedings of 14th JANNAF Combustion Meeting, August 1977, CPIA Publication 292, Vol. I, pp. 235-242, A. Gany, L.H. Caveny, and M. Summerfield.

"Agglomeration and Ignition Mechanisms of Aluminum Particles in Solid Propellants," Proceedings of 17th International Symposium on Combustion, The Combustion Institute, Pittsburgh, PA., Aug. 1978, pp. 1453-1461, A. Gany and L.H. Caveny.

"Breakup of Al/Al_2O_3 Agglomerates in Accelerating Flow Fields," AIAA Journal, Vol. 17, 1979. L.H. Caveny and A. Gany.

"Aluminum Combustion Under Rocket Motor Conditions", Proceedings of AGARD/PEP 53rd Meeting, AGARD-CP-259 April 1979. L.H. Caveny and A. Gany.

"Linear Analysis of Forced Longitudinal Waves in Rocket Motor Chambers", AIAA Paper 79-1210, AIAA Journal. Vol. 19 No. 2, February 1981, pp. 198-204. M.M. Micci, L.H. Caveny, and W.A. Sirignano.

"MHD Measurement of Acoustic Velocities in Rocket Motor Chambers," AIAA Paper 80-1127, AIAA 16th Propulsion Conference, June 30 to July 2, 1980. M.M. Micci and L.H. Caveny; submitted to AIAA Journal for publication.

"Transition to Nonlinear Instability in Solid Propellant Rocket Motors", AIAA Paper 81-1520, July 1981. R.L. Glick, M.M. Micci, and L.H. Caveny.

3.2 Professional Personnel Associated with Research Effort

The professional personnel associated with the research effort were: D.B. Bliss, L.H. Caveny, A. Gany, W.A. Sirignano, and M. Summerfield.

3.3 Interaction with Other Laboratories and Agencies

The research on rocket motor response functions evaluated by means of forced longitudinal waves has stimulated interactions with the Chemical Systems Division (CSD) of United Technologies and with the Huntsville Division of the Thiokol Corporation. Broader interaction with other laboratories occurred through the participation in round robin testing of velocity coupling response measurements being coordinated by Mr. W.C. Andrepont of the Air Force Rocket Propulsion Laboratory.

Portions of the research on aluminum combustion under rocket motor conditions is being applied by Dr. W.N. Brundige of the Elkton Division of the Thiokol Corporation as part of a program sponsored by the Air Force Rocket Propulsion Laboratory and monitored by Mr. W. Roe. Accordingly, twenty high solids Al/Al/HTPB propellants were studied using the techniques associated with cross-flow combustion experiments. This joint effort has resulted in several publications, e.g.

"Reduced Spin Sensitivity HTPB Space Motor Propellants," Proceedings of the 15th JANNAF Combustion Meeting, CPIA Publication 297, Vol. II, pp. 83-104, 1978, W.N. Brundige and L.H. Caveny.

"Combustion of Low Rate HTPB Propellants in an Acceleration Field," to appear in Proceeding of 16th JANAF Combustion Meeting, 1979, W.N. Brundige and L. H. Caveny.

Combustion of aluminized propellants and slag retention has been a consideration in the Air Force's development of the IUS propulsion systems. As a result, L.H. Caveny was invited to give a seminar on aluminum combustion and agglomeration at the [illegible] Corporation on March [illegible], 1979.

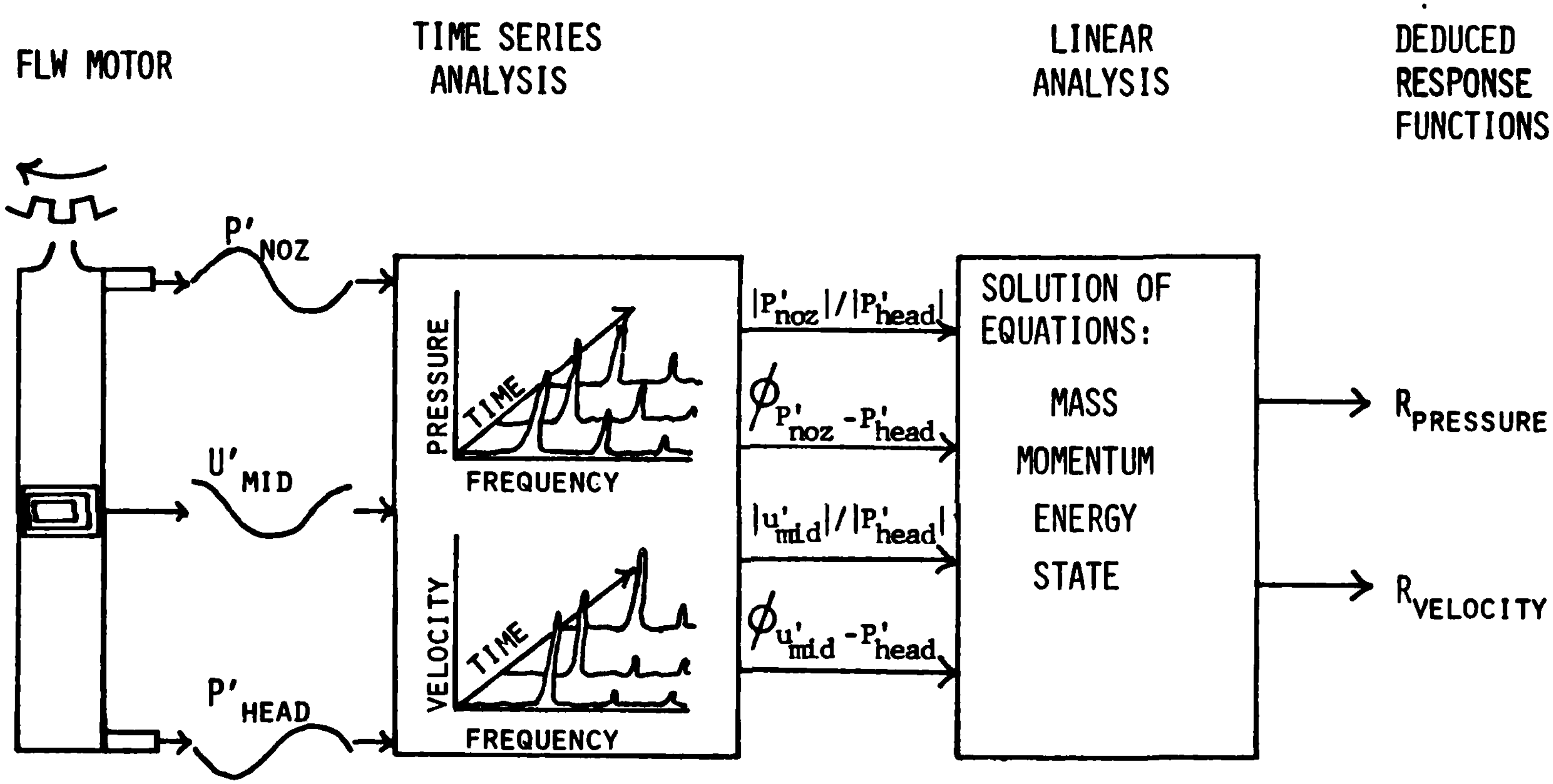
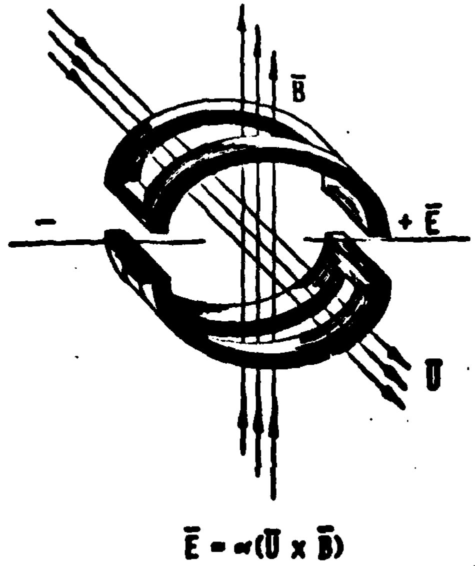
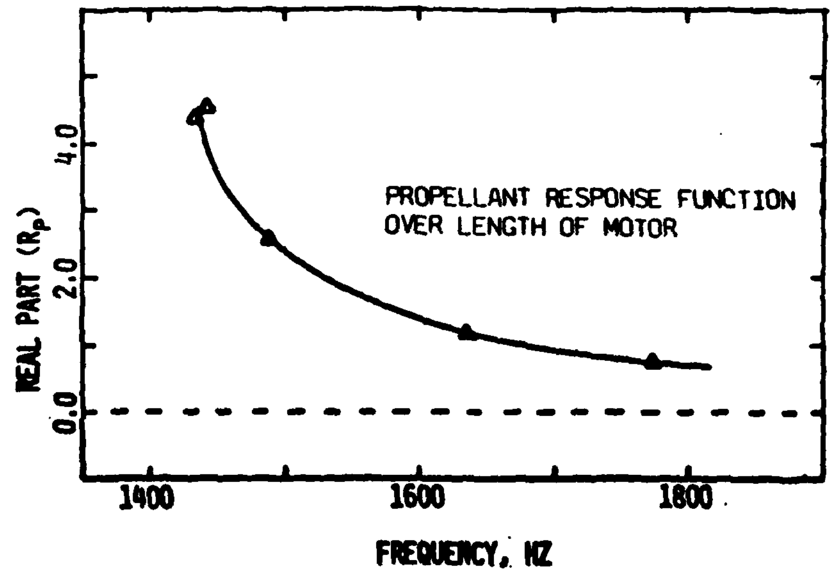


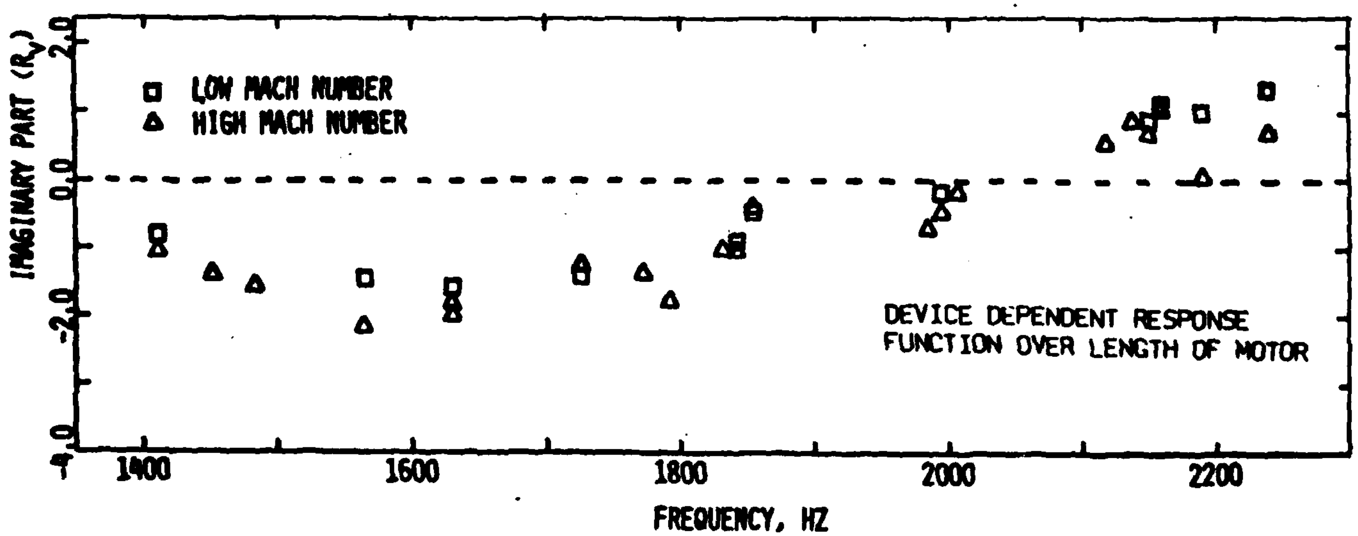
Fig. 1 Pressure- and velocity-coupled response functions simultanously deduced from oscillatory pressure and velocity measurements from a rocket motor firing.



a) Chamber flow velocity measurements (steady and unsteady) were achieved using meter based on Faraday principle.



b) Pressure-coupled response functions deduced from head-end pressure and midchamber velocity.



c) Velocity-coupled response function deduced from head and nozzle pressures.

Fig. 2 Examples of methodology and response function accomplishments.

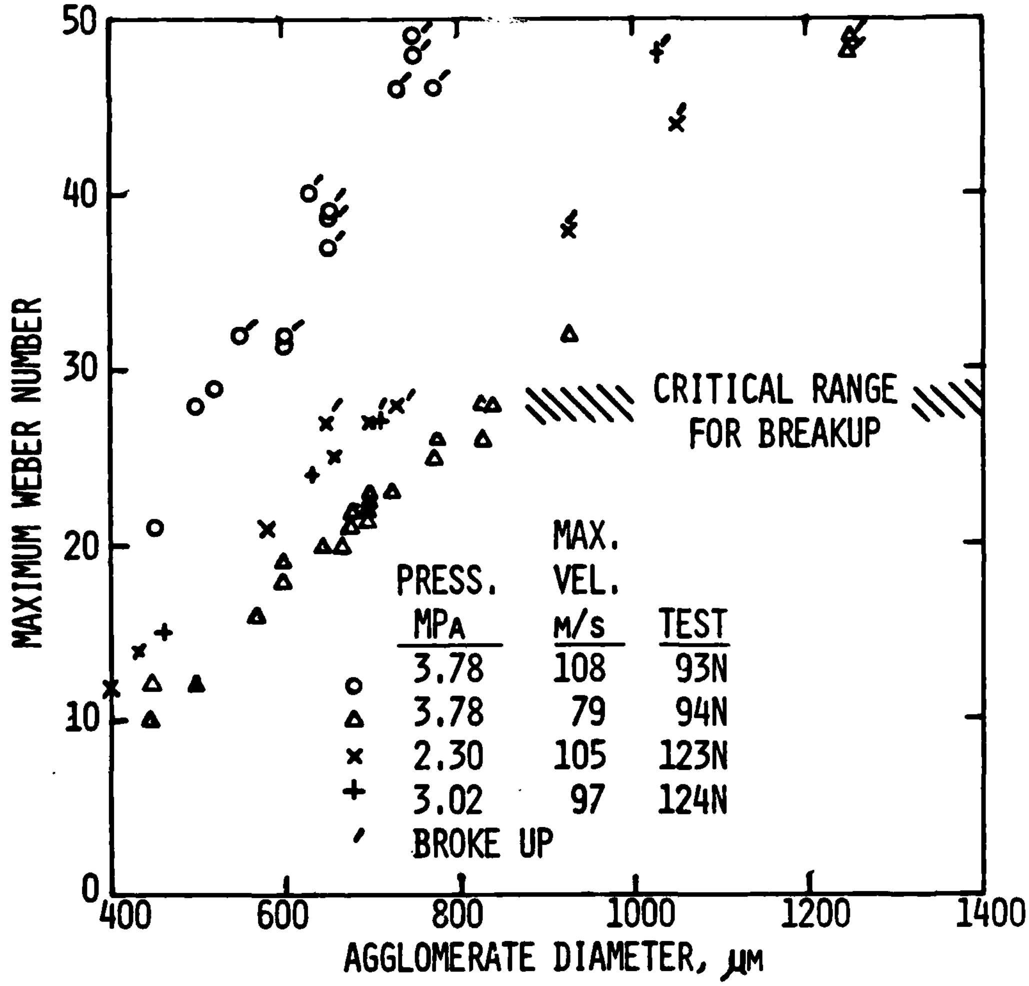


Fig. 3 Agglomerate breakup occurs at sufficiently high Weber numbers.

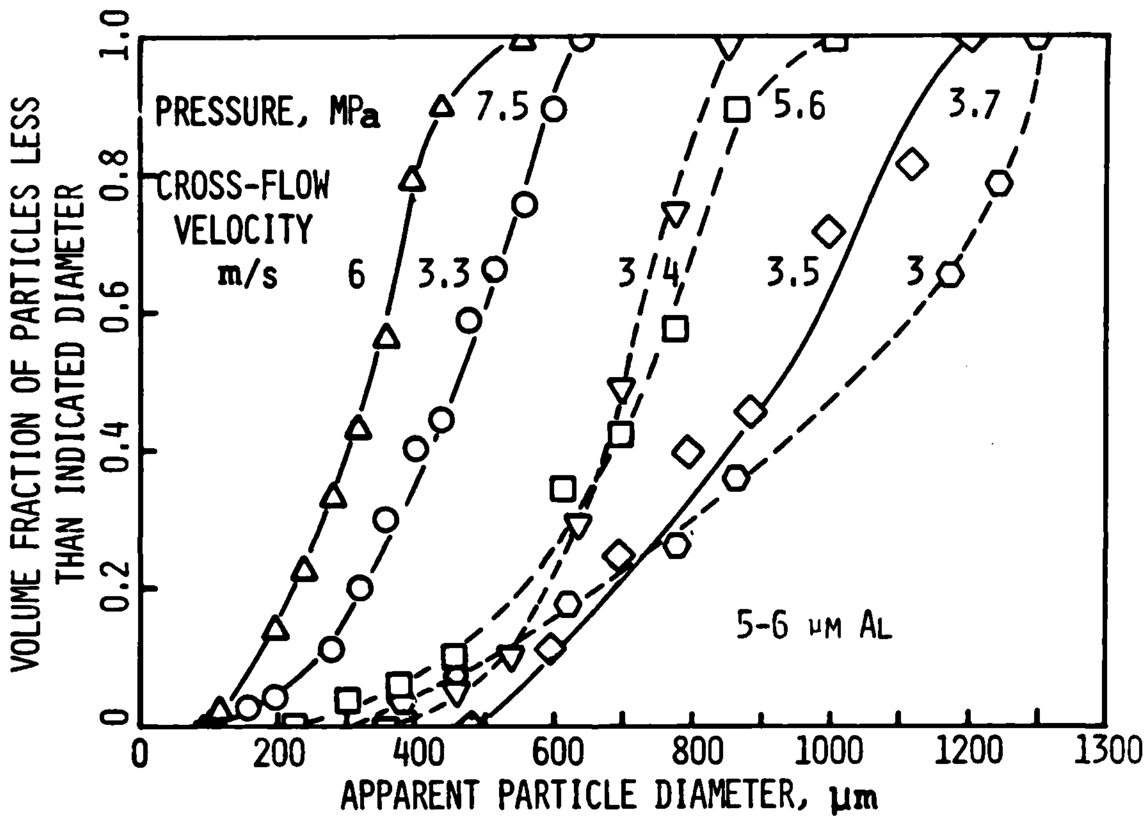


Fig. 4 Volume distribution of agglomerates for a range of motor pressures. Note: (1) decrease of agglomerate size with increasing pressure; (2) some tendency of decreasing particle size with increasing port flow velocity.

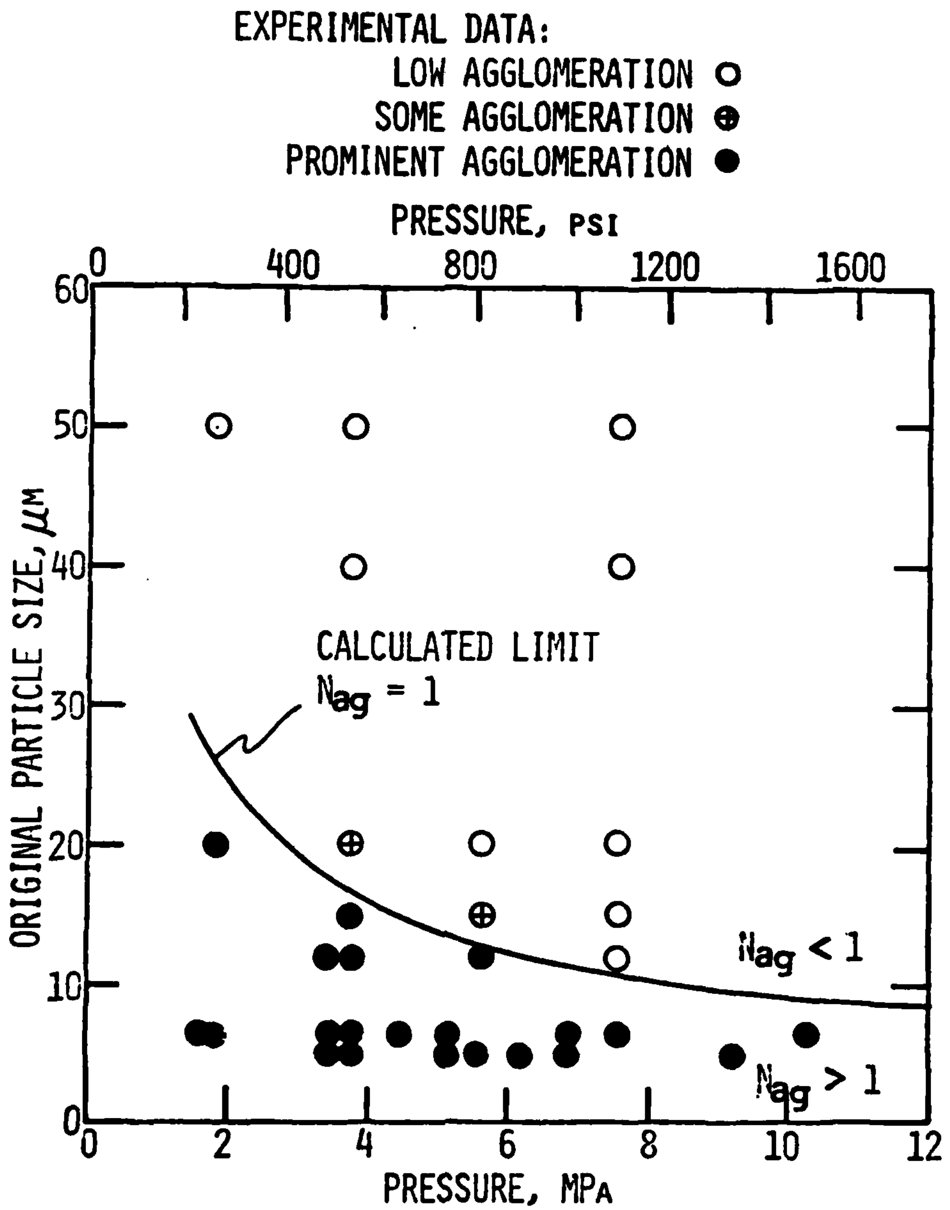


Fig. 5 Agglomeration as a function of particle size and pressure.

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